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LOW COST SOLAR ARRAY PROJECT

PRODUCTION PROCESS AND EQUIPMENT TASK

A MODULE EXPERIMENTAL PROCESS SYSTEM DEVELOPMENT UNIT (MEPSDU)

QUARTERLY REPORT NO. 3
June 1, 1981 to August 31, 1981

CONTRACT NO. 955909

Advanced Energy Systems Division
WESTINGHOUSE ELECTRIC CORPORATION
P. O. Box 10864
Pittsburgh, Pennsylvania   15236

LOW COST SOLAR ARRAY PROJECT
Production Process and Equipment Task

A MODULE EXPERIMENTAL PROCESS SYSTEM DEVELOPMENT UNIT (MEPSDU)

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Contract No. 955909

Approved:

C. M. Rose, Project Manager
Photovoltaic Components

TECHNICAL CONTENT STATEMENT

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I. CONTRACT GOALS AND OBJECTIVES

The objective of this contract is to determine technical feasibility of the production of photovoltaic modules designed to meet all specifications described in JPL Document 5101-138 and fabricated using single crystal silicon dendritic web sheet material. This determination of technical feasibility will be accomplished by:

A. The selection, design, and implementation of a solar cell processing and photovoltaic module assembly sequence in a Module Experimental Process System Development Unit (MEPSDU),

B. Performance of technical feasibility experiments in which 240 modules will be produced in the MEPSDU facility,

C. Passing of acceptance and qualification tests by modules produced during the demonstration runs, and

D. Determination of a 1986 module FOB price of 70¢ or less per watt peak in 1980 dollars as calculated by SAMIS using cost data generated during completion of the demonstration runs (Item B, above).

II. SUMMARY

Work on the Westinghouse MESPDU contract was initiated on November 26, 1980. This report describes work performed during the third three-month period of the contract (June 1, 1981 through August 31, 1981) and outlines plans for the fourth quarter.

Shortly before initiation of the third quarter, direction was received from JPL to modify the contract program plan in order to reduce FY 1981 and FY 1982 spending rates. The resulting program plan accelerated module design and eco- nomic activities while deferring a substantial portion of the process sequence and MESPDU design work during the third quarter. Work was accomplished during this period essentially as scheduled in the revised program plan.

Module design work during this quarter was highlighted by the prototype MEPSDU module design review meeting held at JPL on July 14. A design review data package, prepared in accordance with DR-1 of the Contract Data Requirements List, including copies of viewgraph materials, all module drawings, the module materials selection sheet, performance predictions, and module manufacturing flow information was submitted to JPL prior to the design review.

Subsequent to the design review, a series of tests was conducted on simulated modules to demonstrate that all JPL environmental specifications (wind loading, hailstone impact, thermal cycling, and humidity cycling) are satisfied by the Westinghouse design. All tests, except hailstone impact, have been successfully completed. Hailstone impact simulation tests are currently being devised.

A modified module assembly sequence and module performance analysis were pre- sented at the design review meeting. The assembly sequence was simplified from that which had been presented in the preliminary design review meeting and discussed in the previous quarterly progress report (Westinghouse TME 3110) by virtue of eliminating the frame components and assembly steps. Performance is improved by reducing the module edge border required to accommodate the frame of the preliminary design module.

Although the baseline process sequence remained unchanged from that which was presented in previous reports, investigations of four alternate process steps continued. These investigations are being performed to identify potential improvements to the cost effectiveness of the baseline Westinghouse MEPSDU process sequence.

During the past quarter, an in-depth economic analysis of the baseline Westinghouse MEPSDU process sequence was completed. Using the SAMICS computer code, photovoltaic module production costs were projected for the 1 MW/yr capacity MEPSDU line and a 25 MW/yr capacity production line. The value added was determined for each process step at both levels of production. This analysis has verified that the current baseline process sequence can meet the DOE/JPL cost goals for 1986.

Design work at Kulicke and Soffa on the automated cell interconnect station proceeded as scheduled during the past quarter. An ultrasonic rolling spot bonding technique has been selected for use in the machine to perform the aluminum interconnect to cell metallization electrical joints required in the Westinghouse MEPSDU module configuration. This selection was based on extensive experimental tests and economic analyses. Work on machine concepts for the remainder of the cell interconnect station is proceeding, and an Equipment Specification (E-Spec) has been prepared.

Equipment procurement for the MEPSDU test facility was initiated during this quarter. A combination cell test/module test/data acquisition system and an automated laser scribe were placed on order. These are long-lead items which will not be affected by experimental process sequence design work currently underway.

III. TECHNICAL PROGRESS

A. MEPSDU Module

1. Module Design

The assembly drawing of the prototype Westinghouse MEPSDU module was included in the previous quarterly progress report (Westinghouse TME 3110, Figure 1). This is the module which will be fabricated for the MEPSDU program in the Westinghouse pre-pilot facility and delivered to JPL prior to installation of the MEPSDU facility. Cells for the prototype module will be fabricated using the MEPSDU baseline process sequence; however, minor module dimensional changes may be possible in the final MEPSDU module to take advantage of improved fabrication equipment being procured in the MEPSDU program.

The module design review data package, prepared in accordance with DR-1 of the MEPSDU contract, including copies of viewgraphs, drawings, materials selection sheet, and manufacturing flow information was submitted to JPL in June in conformance with the revised program schedule.

The prototype module design review was conducted at JPL on July 14, 1981. In general, the design was well received. Some concern was expressed by JPL personnel for the unprotected edges of the tempered glass superstrate in the Westinghouse frameless module design. Resolution of this concern was deferred because the problem does not affect the MEPSDU processing line. If glass edge protection is found to be necessary, the internal dimensional modifications necessary to provide wider edge margins on the module are within the capabilities of the MEPSDU equipment; and the resulting reduction in module power output will be factored into the final performance evaluation.

2. Performance Evaluation

Performance evaluation of the prototype MEPSDU module has been completed. Calculations were based on a cell of the dimensions specified in the module drawing package (2.5 cm x 9.8 cm x 0.015 cm) and having the following performance

characteristics at AM1, 91.6 mW/cm^2, and 28°C:

   Short circuit current density = 0.033 A/cm^2

   Open circuit voltage = 0.580 V

   Efficiency = 14.9%

Encapsulation thicknesses and materials in the Westinghouse prototype MEPSDU module are as shown in Figure 1. The calculations were performed using a cell-to-still-air thermal impedance of 300°C/W/cm^2. This thermal impedance was determined experimentally using a small (5" by 8") encapsulated "minimodule" having the MEPSDU module layup configuration. An optical transmission factor of .93 (taken from "Sunadex" glass literature) and an electrical mismatch factor of .975 were assumed for the calculations.

Figure 2 presents four significant module parameters: open circuit voltage, short circuit current, efficiency, and power output plotted as functions of ambient air temperature for operation at AM1.5, 80 mW/cm^2.

Table 1 summarizes the calculated performance parameters for the Westinghouse module at both standard operating conditions (80 mW/cm^2 insolation and 20°C ambient temperature) and at standard test conditions (28°C cell operating temperature and 100 mW/cm^2 insolation level). The latter case defines operating conditions under which the 1986 LSA cost objectives have been defined.

   3.   Environmental Testing

   a.   Hailstone Impact Tests

To study the sensitivity of the unprotected tempered glass superstrate edges, a series of simulated hailstone impacts tests was performed in August. Module-size tempered glass superstrates were used for these tests. Simulated hailstone tests were not performed in strict adherence to JPL Specification 5101-161 because Westinghouse does not have the required ice propelling equipment. If the test results are satisfactory, additional test items will be furnished to JPL for iceball impact tests.

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1/8"	TEMPERED GLASS
.005"	CRANEGLAS
.020"	EVA
.006"	SOLAR CELLS
.020"	EVA
.005"	CRANEGLAS
.003"	MYLAR (KORAD)

Figure 1. Layup Materials and Dimensions of the
Westinghouse MEPSDU Module
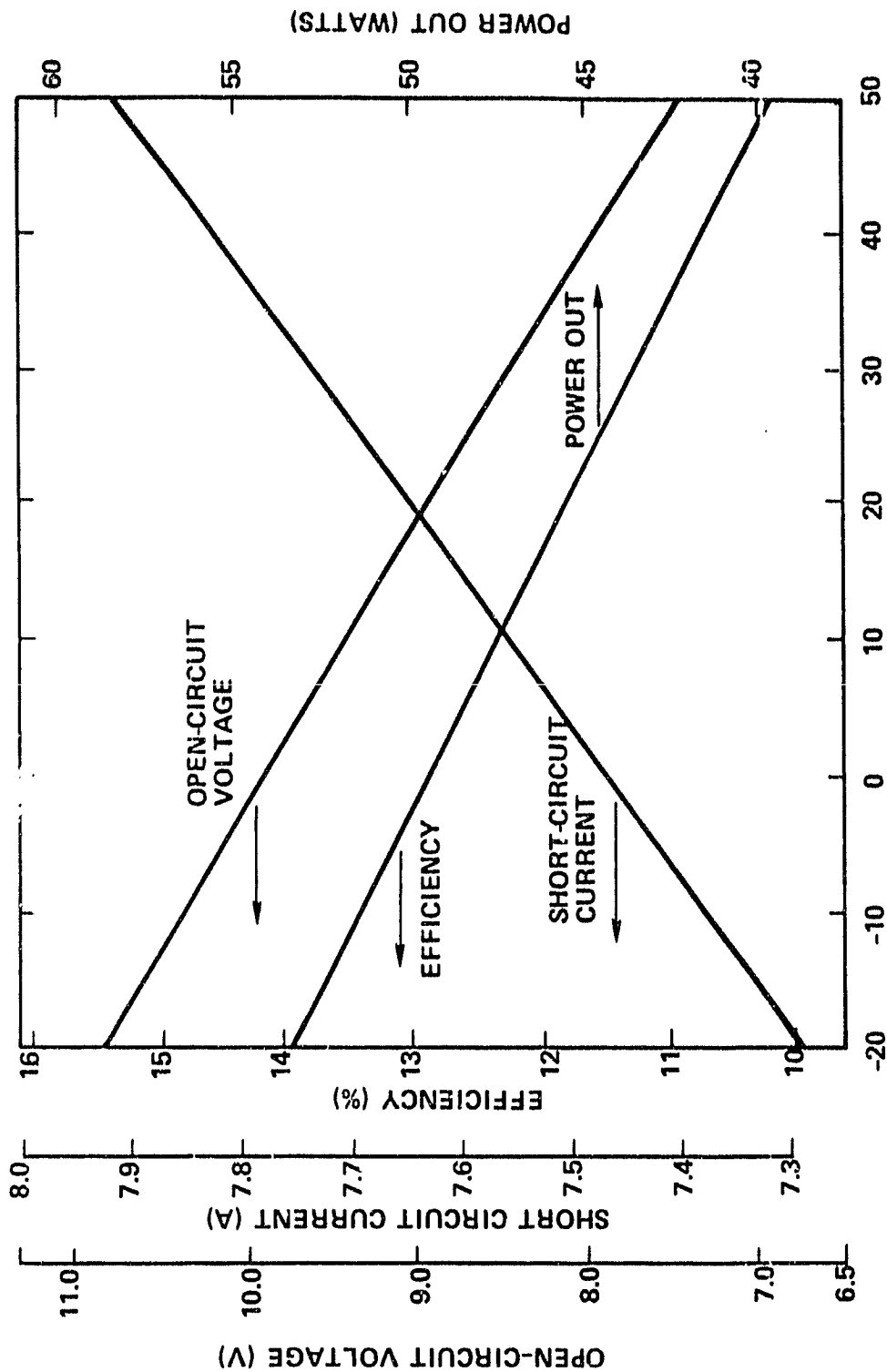
Figure 2. Prototype MEPSDU Module Predicted Performance

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TABLE 1

CALCULATED MEPSDU MODULE PERFORMANCE PARAMETERS

- MODULE OPERATING PARAMETERS AT 80 mW/cm^2; 20°C AMBIENT

  OPEN CIRCUIT VOLTAGE   =   8.16 V

  SHORT CIRCUIT CURRENT =   7.52 A

  POWER   = 44.9 W

  EFFICIENCY   = 11.9 %

  NOM OPERATING VOLTAGE =   6.63 V

- MODULE OPERATING PARAMETERS AT 100 mW/cm^2; AM1.5, AND 28°C CELL OPERATING TEMPERATURE

  POWER   = 59.6 W

  EFFICIENCY   = 12.6 %

In the simulated hailstone impact tests, a 1.1 inch diameter bearing ball (taken from a Stellite underwater bearing) was used as the impacting projectile. The ball was dropped free from various heights, selected so that the ball would impact with a predetermined fraction (up to 100%) of the kinetic energy of the design basis hailstone. The test items used in the initial tests were 1/8 inch thick panels of PPG Industries "Herculite" tempered glass.

In the initial tests, the glass withstood the full (100%) design specification impact in areas away from edges or corners. However, when the ball bearing struck the extreme edge of the glass panel, the glass shattered. It is recognized that the simulated hailstone test is much more severe than the JPL specification in that the steel ball will not deflect as a hailstone, and subsequently, the entire kinetic energy of the impact is absorbed by a concentrated area of the glass. The test did confirm, as was expected, that the glass is more sensitive to impact near its edges than near the center.

Further testing will be performed using a modified projectile to more closely simulate conditions specified by JPL Document 5101-161. The objective of this testing is to determine if edge protection is required to meet hailstone impact specifications and, if so, the amount of glass which must be covered by the edge protection device.

The proposed simulation of the hailstone is a 25.4 mm (1 inch) diameter sphere composed of 62 volume percent fine tungsten metal powder particles bonded together by 38 volume percent ice. These proportions are those expected for random packing of spherical tungsten particles, with the interstices being filled with water. The spheres will be made as sets of two hemispheres in hemispherical cavities in a plastic mold plate with the diametral plane restrained by a second plastic plate. A vent hole through this second plate at the center of the hemisphere will permit expulsion of excess water as the water in the tungsten bed is frozen from the bottom upward. These excess water columns will be broken away from the hemispheres, and two hemispheres will be bonded together by partial thawing and refreezing of the faying surfaces. The ice matrix will be conditioned by thermal soaking at the desired test temperature, -10°C. The

density of the tungsten-ice matrix is 0.443 lb/in^3 (766 lb/ft^3). A one inch diameter sphere of this material dropping 79.2 inches onto the glass surface will deliver 1.53 ft-lbs of energy to the glass surface - the same as the design basis hailstone. The ice sphere will have the same curvature at the point of impact as the design basis hailstone. It will have approximately the same frangibility as the design basis hailstone because it will deform or shatter by failure of the ice matrix. Finally, as the simulated hailstone deforms or shatters and scatters, its kinetic energy will be distributed away from the target point rather than remaining concentrated as in the Stellite bearing ball, reduced only by the energy required to shatter the ice cushion.

The anticipated test plan is:

- testing of Sunadex glass plates, which are now available.

- performing edge and corner impacts with no pre-chilling of the target point, using frangible tungsten-ice pellets having uniformly distributed kinetic energy.

- testing of thicker glass, if necessary to assure panel survival. This would be a trade-off against the cost of a protective frame edge and the value of the reduced energy conversion associated with a frame.

- testing of a survivable panel with functional photovoltaic cells laminated to its back surface. The laminated structure would cover only a small area at the center of the panel, the zone of greatest deflection.

- testing with high-velocity iceball impacts at JPL.

These tests will be initiated in September.

b. Wind Load Testing

In the past quarter, tests were conducted to demonstrate that the 1/8 inch tempered glass superstrate and encapsulated cells of the prototype module can survive both positive and negative wind loading conditions specified by JPL Document 5101-138. In these tests, the frameless module mounting configuration described in the previous quarterly progress report (Westinghouse TME 3110) was used to interface the superstrate glass with the mounting frame.

For the positive wind loading test, the module edge support load equivalent to 125% of the design wind load was transmitted through elastomeric material overlapping the ends of the cells varying amounts, up to 3/8 inch. No damage to the superstrate or any of the cells was observed.

The simulated negative wind loading test, designed to simulate wind loads which would tend to lift the module off its edge support thus placing the structural adhesive attachment in tension, was also successfully performed. The test was conducted on a frameless minimodule that was attached to a support by the double-faced polyurethane tape and silicone structural adhesive with which the modules will be mounted in test and service installations. The back face of the mini-module was loaded by a uniformly distributed layer of fine tungsten powder (enclosed in a thin plastic bag and restrained laterally by vertical plastic dams). The depth of the tungsten powder, 9 inches, was sufficient to develop a restraining tensile force of 25 lbs per lineal foot of the module edge, applied to the module through the structural adhesive bond to the back face of the module encapsulation. This tensile force is the same as a 50 lb/ft^2 wind load will develop on a full-size module. The load was sustained for fifteen minutes, rather than for one minute as the specified gust loading, with no indications of tearing, separation, or creep in the support attachment.

c. Laminate Environmental Testing

Twelve minimodules were assembled for environmental testing using cells produced on the Westinghouse pilot line with efficiency levels unacceptably low for incorporation into modules. These small modules were made to evaluate the ability of several different layups to withstand test conditions specified in JPL 5101-138. Lamination and the results of thermal cycling tests performed according to JPL 5101-138, Figure 5.1, were reported in the previous quarterly report (Westinghouse TME 3110). The layup of each of the small modules used for environmental testing is given in Table 2 of this report.

All twelve small modules, after completion of 50 thermal cycles per JPL 5101-138, Figure 5.1, were placed in an environmental test chamber and subjected to the humidity test conditions defined by JPL 51-1-138, Figure 5.2. The modules were inclined at 45° during the test. The modules and the holding fixture are shown in Figure 3.

TABLE 2

LAYUP OF SMALL MODULES USED FOR ENVIRONMENTAL TESTING

G-1 (1.6 x 9.4 cm cells)	G-2 (1.6 x 9.4 cm cells)	G-3 (1.6 x 9.4 cm cells)	G-4 (1.6 x 9.4 cm cells)	G-5 (1.6 x 9.4 cm cells)	G-6 (1.6 x 9.4 cm cells)
Window Glass	Window Glass	Window Glass	Window Glass	Window Glass	Window Glass
Craneglas	EVA	Craneglas	Craneglas	Craneglas	Craneglas
EVA	5 Cell String	EVA	EVA	EVA	EVA
5 Cell String	Craneglas	5 Cell String	5 Cell String	5 Cell String	5 Cell String
Craneglas	EVA	Craneglas	Craneglas	Craneglas	Craneglas
EVA	Craneglas	EVA	EVA	EVA	EVA
Craneglas	Korad-KLEAR	Craneglas	Craneglas	Craneglas	Craneglas
Korad-KLEAR	Tedlar Edge Tape	White Korad	Clear Tedlar (2 mil)	Clear Tedlar (4 mil)	White Tedlar (2 mil)
			Tedlar Edge Tape		

G-7 (1.6 x 9.4 cm cells)	G-8 (1.6 x 9.4 cm cells)	G-9 (1.6 x 9.4 cm cells)	G-10 (1.2 x 10 cm cells)	G-11 (1.2 x 10 cm cells)	G-12 (1.2 x 10 cm cells)
Window Glass	Window Glass	Window Glass	Window Glass	Window Glass	Window Glass
Craneglas	Craneglas	Craneglas	Craneglas	Craneglas	Craneglas
EVA	EVA	EVA	EVA	Elvax	EVA
5 Cell String	5 Cell String	5 Cell String	5 Cell String	5 Cell String	7 Cell String*
Craneglas	Craneglas	Craneglas	EVA	Elvax	EVA
{EVA Primed Clear	{EVA Primed White	EVA	Craneglas	Craneglas	Craneglas
Tedlar (2 mil)}	Tedlar (2 mil)}	Craneglas	White Korad	White Korad	Korad-KLEAR
		Acrylar X-22417			
		Tedlar Edge Tape			

*K&S bonded

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Figure 3. Environmental Test Modules in Humidity Test Fixture

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Open circuit voltage and short circuit current measurements were made on each of the modules within one-half hour after the completion of the humidity test. These data are compared to obtained as-laminated and after 50 thermal cycles in Table 3. Differences seen in the data are within the measurement error of our equipment. The differences, if any, on the performance characteristics of the small modules subjected to the environmental tests specified in JPL 5101-138 are not measurably significant.

Each of the modules was examined after the thermal cycling tests, and comments on areas containing small defects were made in the previous quarterly report (Westinghouse TME 3110). A re-examination of each of the modules after the humidity test indicated that, except for a slight darkening of the external copper leads, there was no noticeable change in the appearance of the modules as a result of the humidity test.

Thermal and humidity cyclic testing of these modules will continue to study long-term effects, if any, of varying environmental conditions on the MEPSDU module lamination configuration.

d. Loss of Cell Contact Pad Electrical Connection

Front surface (sun side) current collection from cells incorporated in the Westinghouse MEPSDU module design is achieved with a series of very fine (1 mil wide) straight conductors emanating from contact pads along one edge of each cell. Cell-to-cell electrical interconnection is achieved by bonding aluminum conductors to each of the contact pads. The fine lines are parallel connected on the surface of the cell so that if the electrical connection to a pad fails, the photocurrent can be collected by neighboring pads albeit with a somewhat higher resistance. This redundancy of contacts leads to a high tolerance to interconnect failure.

To quantify the effect of interconnect failure, several tests were made where the change in the cell output power was determined as a function of the number of pads contacted.

TABLE 3

MEASUREMENTS MADE ON ENVIRONMENTAL TEST MODULES

Module No.	Open Circuit Voltage			Short Circuit Current		
	As Laminated	After 50 Thermal Cycles	After Humidity Test	As Laminated	After 50 Thermal Cycles	After Humidity Test
G-1	2.58	2.52	2.56	.318	.337	.338
G-2	2.58	2.60	2.60	.278	.285	.301
G-3	2.57	2.61	2.62	.326	.345	.338
G-4	2.46	2.60	2.60	.330	.330	.335
G-5	2.48	2.52	2.53	.246	.256	.258
G-6	2.52	2.57	2.58	.262	.272	.277
G-7	2.51	2.57	2.56	.265	.271	.272
G-8	2.54	2.60	2.60	.267	.283	.277
G-9	2.58	2.64	2.64	.330	.335	.333
G-10	2.66	2.69	2.70	.283	.294	.292
G-11	2.69	2.71	2.72	.295	.299	.294
G-12	3.75	3.75	3.80	.273	.272	.272

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To carry out the test, cell parameters were first measured with all 10 inter-connect pads being contacted. The test was then repeated 7 times with the number of pads contacted being reduced by 1 in each test. Table 4 shows the design and results of this experiment. The first three columns of Table 4 show which pads were contacted during the test: the last column shows the output power of the cell at the test conditions.

The power decreased by only 3% when nine pads were contacted and by 7% with only seven pads contacted. With only three pads connected, the power decreased by less than 50%. The major causes of the power loss were the decrease in the fill factor and short circuit current due to the added series resistance of the cell. The thin grid lines in this experiment were conducting the photo-current over several centimeters, thereby increasing the resistance.

The results given would change if different sequences of pad numbers were con-tacted. For example, the power output when pads 4, 5, and 6 were contacted would be greater than if pads 1, 2, and 3 were contacted.

These data, however, do show that several interconnection contacts can be lost in a cell without significantly decreasing the power; and thus the cell design does shows a high tolerance to interconnect failure.

e. Cell Shading Tests

The ability of the prototype MEPSDU solar cell string to survive the short circuit/shaded cell tests specified in JPL Document 5101-138 was discussed in the previous quarterly report. During this quarter, additional cell shading tests were performed using the 5 cell modules (1.6 cm cells) that were prepared for environmental testing. Three of these modules were connected in series to simulate the 15 cell string of the MEPSDU module. Each cell was then shaded, one at a time, with the modules operating in normal sunlight conditions. Figure 4 shows a typical test system used for the shading tests. Figure 5 shows the change in temperature (measured on the back cover behind each of the cells) with time and incident power for a test in which the center cell of each 5 cell

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TABLE 4

OUTPUT POWER FROM SOLAR CELL AS FUNCTION
OF INTERCONNECT PADS CONTACTED

Test #	No. of Pads Contacted	Pad No. Contacted*	Cell Power - Out (watts)
1	10	1,2,3,4,5,6,7,8,9,10	0.162
2	9	1,2,3,4,5,6,7,8,9	0.158
3	8	2,3,4,5,6,7,8,9	0.152
4	7	2,3,4,5,6,7,9	0.152
5	6	2,4,5,6,7,9	0.146
6	5	2,4,5,7,9	0.145
7	4	4,5,7,9	0.117
8	3	4,5,7	0.087

*Pad No. Definition

1   2   3   4   5   6   7   8   9   10
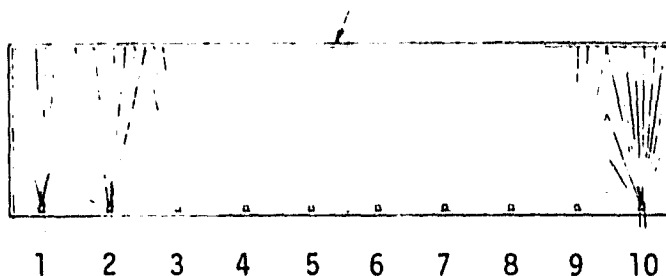
Figure 4. Test System Used for Cell Shading Tests
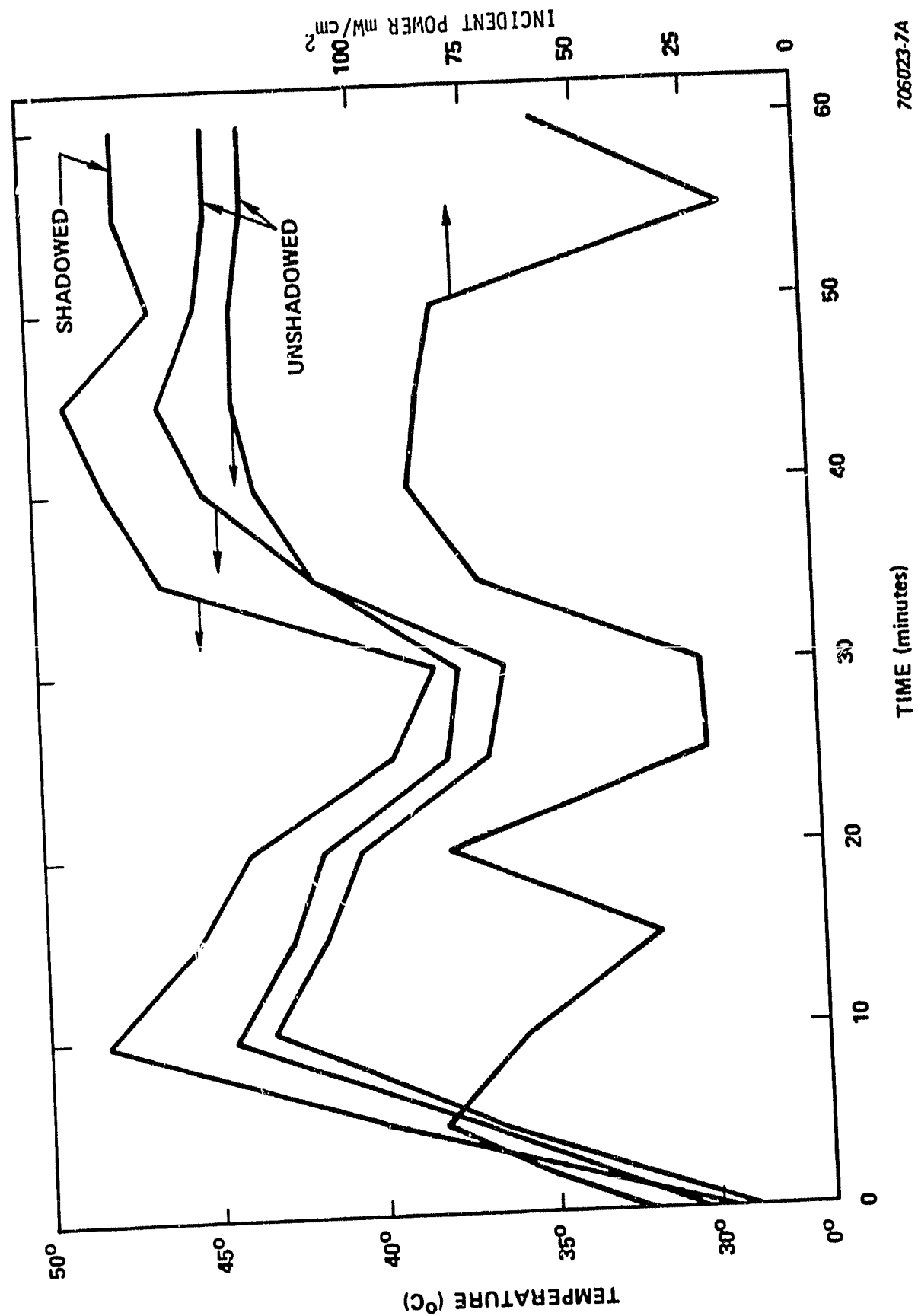
Figure 5. Shadowed Cell Heating Effects under Module Short Circuit Conditions

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module of the 15 series connected cells was monitored. Both the shadowed and unshadowed cells responded to changes in incident power, and progressive over-heating of the shadowed cell did not occur. In fact, in some tests the shadowed cell ran slightly cooler for corresponding insolation values than it did in the unshaded condition. These data reinforce the conclusions that were reported in the previous quarterly, i.e., that destructive overheating of a shaded cell during short circuit operation of a module is not a problem with the high current module design with 12 strings of 15 series connected cells. Further tests are planned using a continuous 15 cell string of 2.5 cm cells in a layup precisely duplicating the electrical circuit of the MEPSDU module.

4. Module Assembly

Recent changes in the module design and advances in the design of the bonding station have resulted in a module manufacturing flow chart that contains fewer steps than that presented in Quarterly Report No. 1 (November 26, 1930 to February 28, 1981) and at the preliminary design review on March 4, 1981. The revised flow chart, shown in Figure 6 and presented at the module design review on July 14, 1981, consists of the following operations:

a. Superstrate Preparation - Sized, low iron tempered drawn glass is cleaned with a commercial glass cleaner and posi-tioned with the fine matte surface down in the first posi-tion of the automatic interconnect station. The coarse matte surface of the opposite side is primed with a dilute solution of an organofunctional silane and dried with warm air.

b. Sunside Layup Installation - A spacer of Cranelgas is placed on the primed glass surface. Ethylene vinyl acetate (EVA), used as a lamination pottant, is placed on the Craneglas. The sunside layup is then transferred to the second position of the automatic interconnect station.
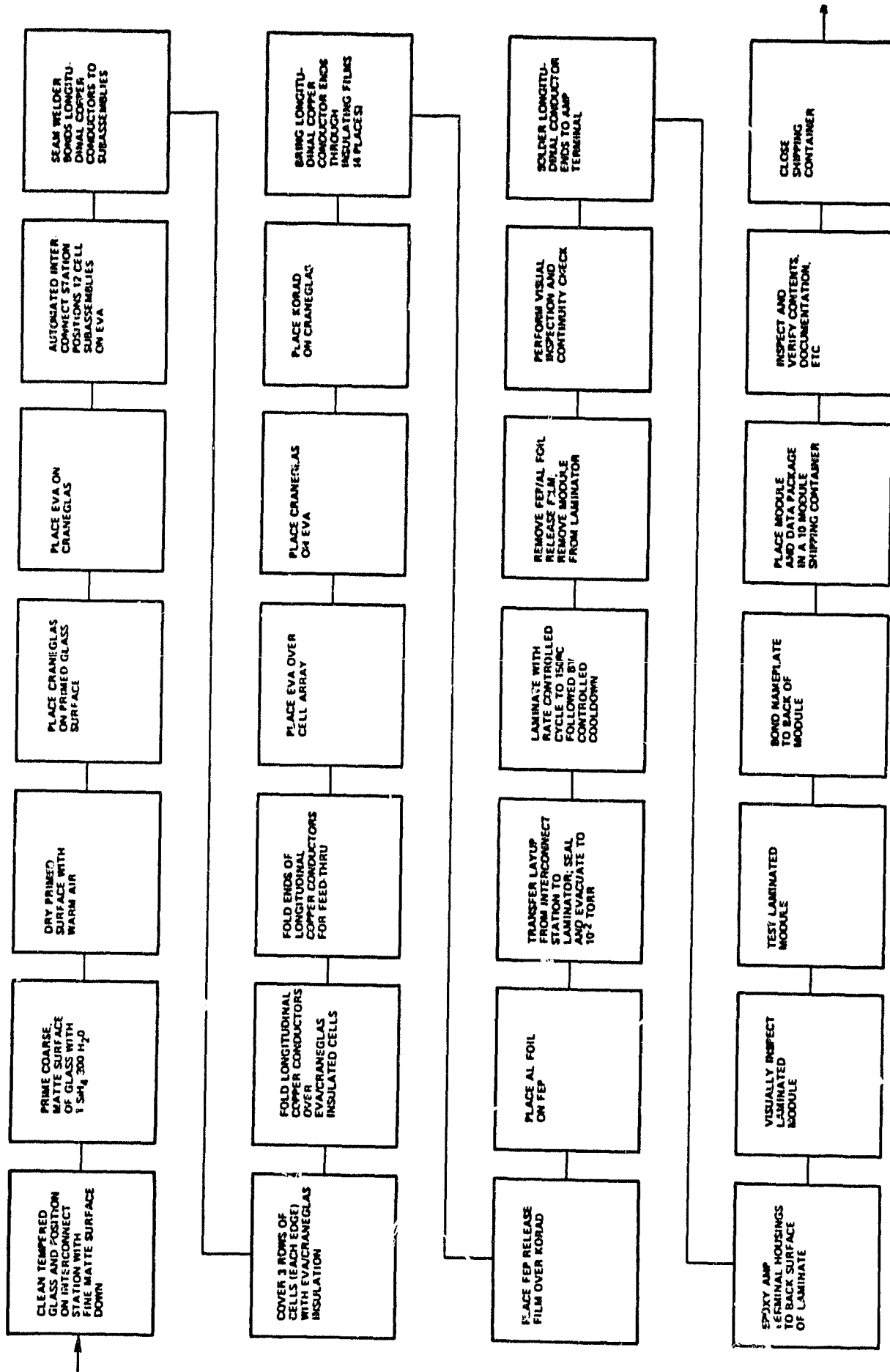
Figure 6. Module Assembly Flow Chart

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c. Bonding and Positioning of Cell Subassemblies - In the cell stringing and tabbing machine, aluminum interconnects are used to electrically join the front side of each cell to the back of another. An ultrasonic rolling spot bonder is used to form a series string of 15 interconnected cells. Twelve of these series strings are automatically positioned by the automated tabbing and stringing machine on the EVA of the sunside layup. This subassembly is then moved to the third position of the automatic interconnect station.

d. Installation of Longitudinal Conductors - The end inter-connect tabs from each of the twelve series strings are ultrasonically seam welded to longitudinal copper conductors. Three rows of cells on each edge of the strings are covered with EVA/Craneglas to insulate the cells from the longitud-inal conductors as they are folded back over the cells and brought into a position where the ends of the conductors can be brought to the dark side layup.

e. Dark Side Layup Installation - A layer of EVA pottant is placed over the cell array. This is followed by the positioning of a layer of Craneglas, positioning of a name-plate, and installation of the back cover film of Korad. The ends of the copper longitudinal conductors are brought through each of these insulating films as they are placed in position. The final layup is transferred (sunside down) to the vacuum laminator.

f. Lamination - Release films of aluminum foil and fluorinated ethylene propylene copolymer (FEP) are placed over the module layup. The laminator is sealed and evacuated to 10^{-2} torr. It is heated to 110°C in less than 30 minutes, vented, heated to a maximum temperature of 150°C, and then cooled to room temperature. The FEP/Al foil release films

are removed, and a visual inspection and electrical continuity check performed.

g. Electrical Terminal Installation - Pre-tinned electrical terminal end conductors are soldered to the two bus bars. The back cover/end conductor penetrations are enclosed by a conductor housing that is attached to the back surface of the laminate using an epoxy adhesive formulated for this service.

h. Inspect and Test - A visual inspection of the assembled module is performed, and the current-voltage characteristics of each module are measured at AM1, 100 mW/cm^2 and 28°C.

i. Module Packaging - Acceptable modules are crated for shipping. Each shipping container holds ten modules and their respective data packages. The contents of each shipping container are verified, and the container is closed.

B. Process Sequence Design

The preliminary "baseline" process sequence for the Westinghouse MEPSDU has remained unchanged from that which was presented at the preliminary design review held in March and outlined in the initial quarterly progress report (Westinghouse TME 3090). During the past quarter, investigations were continued into four selected areas of the sequence in an attempt to demonstrate the potential for reducing processing costs below the level evaluated for the baseline sequence. Areas being investigated include: alternate, more cost-effective metallization procedures; ion implantation of front and back junctions to replace the diffusion and its associated masking/cleaning steps; liquid precursor films for diffusion masks and dopants; and dry processing (plasma etching) to reduce wet chemical usage. Each of these areas will be discussed in further detail.

1. Metallization Process Selection

Experiments on the utilization of electroless nickel in the metallization process sequence continued throughout the quarter. In-house scoping experiments indicated that electroless nickel deposition on evaporated titanium and on activated silicon are feasible provided that the etching and surface activation can be controlled to the extent that they will not destroy the shallow cell junction or the AR and PR coatings normally applied before metallization. Two vendors volunteered to pursue these approaches in their laboratories with negative results.

In the first case, that of electroless nickel deposition on evaporated titanium, the etchants employed by the vendor were too aggressive and etched through the evaporated 300-500 Å titanium film. This approach was abandoned. In the second case, that of electroless nickel deposition on silicon in the presence of AR and PR coatings, both vendors cited attack of the PR coating in the heated (approximately 90°C) electroless nickel baths. (Both vendors were working with silicon web that was supplied to them by Westinghouse after AR/PR coating, pattern exposure, development, and oxide etching. The PR coating had received the standard soft bake for 15-20 minutes at 90°C.)

Subsequent work continued with one of the vendors on the deposition of electroless nickel on silicon. Investigations included: (1) deposition of electroless nickel on a patterned sample given a post-bake treatment to improve the chemical and heat resistance of the PR coating, and (2) deposition of electroless nickel on silicon followed by the use of a negative resist.

A proprietary, highly alkaline nickel activating solution that showed promise on bare silicon was found to be too sensitive to deposition conditions to be used as a production process. Because the solution was highly alkaline, it also attacked the post-baked positive PR coating and, therefore, cannot be used on partially processed samples. Additional work by the vendor yielded a new process that is claimed to be very reproducible with very few voids and with improved adhesion to silicon. Further work will be done in September to evaluate this process.

In addition to work on an alternate metallization system, an experiment was successfully completed on the evaporated Ti/Pd, plasma ashed, electroplated copper baseline process in which the Ti thickness was increased to 800 Å. Additional tests are planned to establish the most effective ratio of the metallized layers.

2. Ion Implantation Studies

a. Background

The baseline MEPSDU process specifies thermal diffusion processes for formation of the front and back junctions of the solar cell. These processes have been shown capable of producing high efficiency cells and have been standard in the semiconductor industry for many years. SAMICS calculations discussed in a later section of this report have confirmed that the JPL-LSA 1986 cost objectives can be achieved using a process sequence that includes two diffusion steps.

However, preliminary investigations carried out at the Westinghouse R&D Center in conjunction with the Advanced Energy Systems Division indicate that ion implantation of one or both junctions could improve the production cost effectiveness of the MEPSDU process. This increased cost effectiveress would result from the production of a higher efficiency cell coupled with decreased production costs.

To further investigate the potential advantages associated with ion implantation, a Westinghouse funded experiment was carried out at Spire Corporation in Bedford, Massachusetts. The purpose of this experiment was to allow a comparison of efficiencies and performance reproducibility characteristics of ion implanted dendritic web solar cells with the standard diffused junction solar cells.

The ion implantation was made on 100 dendritic web silicon strips, each 2 cm wide (or greater) by 11.4 cm long, and 175 ±25 μm thick. The entire central area of the web strip was implanted so that 1.6 cm x 9.4 cm cells could be fabricated and evaluated.

In general, the fixturing in ion implantation equipment is specifically designed for round wafers and not immediately usable for the rectangular dendritic web. Thus, the initial phase of the Spire program was to design and fabricate web holding fixtures compatible with their ion implantation equipment. During the initial testing of this fixture and early implantation, a significant number of web strips were broken reducing the number of cells available for evaluation.

The implantation and annealing parameters used for the cells were as follows:

Phosphorous: 10 KeV, $2.5 \times 10^{15} \frac{P \text{ atoms}}{cm^2}$

Boron: 25 KeV, $5 \times 10^{15} \frac{B \text{ atoms}}{cm^2}$

Anneal: Resistance furnace with flowing N_2

        650°C - 2 hours

        850°C - 15 minutes

        650°C - 2 hours

These implantation and annealing parameters, which were derived from experience on [100] Cz wafers, were selected to allow an initial assessment of the potential advantages of the ion implantation junction formation process. No attempt was made to optimize the parameters for [111] dendritic web. With the parameters listed above, the sunside n+ junction depth is nominally 0.2 μm while the back side p+ junction depth is nominally 0.5 μm.

For this ion implantation experiment, half of the web strips were to be returned to Westinghouse after annealing for cell processing and measurement. They were then returned to Spire for measurement. The remaining strips were processed by Spire Corporation through metallization, returned to Westinghouse for cell separation (laser scribing), and then returned to Spire for application of an antireflective coating and measurement. This group of cells was also measured at Westinghouse after laser scribing.

b. Test Results from Cells Implanted and Processed by Spire

Table 5 shows the average parameters measured by Westinghouse for the 15 cells ion implanted and processed by Spire. Cell efficiencies, adjusted to reflect a 45 percent antireflective coating enhancement, fell in the range 12.57 ±.78%.

c. Cells Ion Implanted by Spire and Processed by Westinghouse

The remaining web strips were returned to Westinghouse after ion implantation and annealing for cell processing. This processing included all steps in the Westinghouse MEPSDU process sequence after the junction formation process.

The sheet resistivity on all of these web strips was measured prior to cell fabrication. The back surface resistivity varied from 65 - 80 $\Omega/\square$ while the front surface resistivity varied from 55 - 75 $\Omega/\square$. Both of these values are in the required range of the Westinghouse dendritic web diffused junction specification.

Due to processing losses, breakage during shipping, and improper implantation (cells marked incorrectly and processed with the grid pattern on the back side), a total of 30 cells were available for measurement. The results are shown in Table 6. Cell efficiencies fell in the 12.73% ±1.04%. Two cells were excluded from the averages given in Table 6 since their efficiencies were less than 5%.

d. Discussion

Due to breakage, labelling problems, and web availability, sample sizes were too small to allow a thorough statistical evaluation of results; but several comments can be made. First, the level of reproducibility (from cell to cell) in the ion implanted sample did not meet our total expectations. However, the ion implanted samples were fabricated on a number of different web crystals; and it is not clear whether the ion implanted cell variations are associated with the junction formation process, subsequent processing operations, or initial material differences. Second, in a number of cases (about 60% of the total cells processed), it was possible to compare data for cells produced by the diffusion process and the ion implantation process on the same web

TABLE 5

AVERAGE CELL PARAMETERS - CELLS ION IMPLANTED
AND PROCESSED BY SPIRE CORPORATION*

$$I_{sc} \text{ (A)} \quad - \quad 0.325 \pm 0.014$$

$$J_{sc} \text{ (A/cm}^2\text{)} \quad - \quad 0.0216 \pm 0.002$$

$$V_{oc} \text{ (V)} \quad - \quad 0.550 \pm 0.008$$

$$P_{max} \text{ (watts)} \quad - \quad 0.130 \pm 0.008$$

$$\eta\text{(\%)} \quad - \quad 8.67 \pm 0.53$$

*Measured at 100 mW/cm^2, AM1 - No antireflection coating.

(If a nominal enhancement of 1.45 is assumed for the anti-
reflective coating, the efficiency would be 12.57 $\pm$0.78%.)

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TABLE 6

AVERAGE CELL PARAMETERS - CELLS ION IMPLANTED BY
SPIRE AND PROCESSED BY WESTINGHOUSE*

I_{sc} (A)   - 0.471 ±0.023

J_{sc} (A/cm^2)   - 0.0313 ±0.0015

V_{oc} (V)   - 0.559 ±0.008

P_{max} (watts)   - 0.191 ±0.015

$n(\%)$ - 12.73 ±1.04

*Measured by Westinghouse AESD at 100 mW/cm^2, AM1.
  Antireflection coated.

crystal. In these cases, the ion implanted cells had an average efficiency of 12.7% ±0.9% while the diffused samples measured 12.2% ±0.8%, an improvement of .5% absolute efficiency.

From the results of this program, the following tentative conclusions are drawn:

1. Cells fabricated from web with ion implanted junctions are superior to cells with diffused junctions (perhaps by 0.5% absolute efficiency).

2. The ion implantation process is compatible with the MEPSDU process sequence although fixturing is required so that web lengths up to 42 cm long can be implanted.

3. Further work is required before the ion implantation process could be qualified for the MEPSDU process sequence. In addition, a cost analysis of the ion implantation method is required.

3. Liquid Precursor Films for Diffusion Masks and Dopants

The intent of this task is to identify modifications to the baseline diffusion process sequence which can reduce costs by using less expensive chemicals, less involved procedures, simplified equipment and controls, and improve the automatability of the process.

The first experiment in this task was performed to study feasibility of substituting a liquid applied film as a diffusion mask replacing CVD (chemical vapor deposited) SiO_2 in the baseline processes sequence.

In the initial experiment, described in the previous quarterly report (Westinghouse TME 3110), the Westinghouse antireflective (AR) coating (a TiO_2-SiO_2 solution in alcohol) was used as a diffusion barrier. Test data from the cells processed in this experiment indicated that the antireflective coating does act as a diffusion mask in that the measured cell parameters from the two groups were the same. However, the etching behavior of the coating precludes it use in a production facility.

A second diffusion barrier experiment was performed during this quarter in which a modified Westinghouse AR coating was used as a diffusion barrier. This solution contained only an SiO_2 precursor, and the film formed from this solution did not compltely oxidize in the diffusion furnace. Therefore, in contrast to cells masked using the standard Silox process, the cells were contaminated with carbon and gave very poor results in the subsequent gaseous diffusion processing steps. Based on these negative results, attention has been directed to the identification of a liquid dopant process wnich could eliminate the need for application of a diffusion mask.

Various experiments were performed in August using Borofilm 100 and Phosphoros N-250 liquid sources bought from Emulsetone, Inc. Attempts at one-step paint on diffusion were not successful in that cross-contamination of dopants was observed. The diffusion temperature used for this experiment was 960°C which is the same as the open-tube BBr_3 process.

The next set of experiments was made using a two-step paint on and diffusion process. The sequence of operation for these experiments was as follows:

1. Apply Borofilm 100 on one side of cleaned web with a fine brush and bake at 200°C for 15 minutes.

2. Start flow of N_2 (2000 cc/min) and O_2 (500 cc/min).

3. Load web into diffusion boat, insert very slowly in the furnace hot zone and diffuse at 960°C for 35 minutes.

4. Pull the diffusion boat slowly from furnace to maintain a cooling rate less than 3°C/min.

5. Deglass one small piece and measure sheet resistance.

6. Using web pieces which are not deglassed, apply N-250 Phosphoros on the nondiffused side of the web and bake at 100°C for 15 minutes and 200°C for 15 minutes.

7. Load web into diffusion boat, insert very slowly in the furnace hot zone and diffuse at 960°C for 15 minutes.

8. Pull the diffusion boat very slowly from the furnace to maintain a cooling rate less than 3°C/min.

9. Deglass the sample pieces and measure sheet resistance.

Using the above process, N+ and P+ junctions were achieved on the test samples. The sheet resistance measured on the P+ side was 27 $\Omega/\square$ and on the N+ side was 14 $\Omega/\square$. These sheet resistances were lower than the desired level of 50 $\Omega/\square$ (both sides).

Additional experiments are planned for the upcoming quarter. In these experiments, processing times and temperatures will be varied to achieve the desired junction depths. Web diffused in these experiments will be processed into cells using the Westinghouse pre-pilot facility. If results are positive, a meniscus-coating of the diffusant liquids will be attempted to improve uniformity.

4. Dry Processing

Screening tests were performed by a vendor to establish conditions for cleaning raw web by plasma processing. Their findings using the standard $96/4:CF_4/O_2$ etching gas were similar to ours in that, without prior oxide removal, the silicon surface is not uniformly etched. Table 7 summarizes their results.

TABLE 7

PLASMA ETCHING OF RAW WEB

Plasma	Pressure (torr)	R. F. Power (watts)	Time (min.)	Comments
Argon	.4-.6	300-500	2-15	No reaction.
$96/4:CF_4/O_2$	.3	300	2-6	Non-uniform surface attack.
$30/70:CF_4/O_2$	.1-.3	85-400	1-50	Best results obtained at 85W and times in excess of 5 min.
$5/95:CF_4/O_2$	.3-.4	250-350	5-10	Surface clouding due to excess oxidation.

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After 50 min. of testing with a 30/70:CF_4/O_2 plasma at 85 watts R.F. power, there was no SiO_2 powder present, and, although there was a suggestion of a nonuniform adherent oxide, the surface had a reflectivity similar to web cleaned by standard wet chemical techniques. However, the time is considered excessive for cost effective processing; and, therefore, a combination of wet chemical/plasma etch processing will be pursued.

An ultrasonically agitated HF dip has been found to be inadequate in that it does not readily remove both the loose and adherent oxide, and an HF scrubbing station may be required. However, before committing to a scrubbing station, additional tests are being performed with other acid solutions and a variation of cleaning procedures. Verification runs combining the wet chemical cleaning with plasma etching are underway.

C. MEPSDU Design

This task is associated with the design or specification of equipment required to perform all operations of the Westinghouse process sequence. Most tasks in this element of the program have been deferred into the next quarter due to JPL FY 1981 budget reductions. However, this section of the report summarizes the current status of each task.

1. Junction Formation Station

An equipment specification (E-Spec) has been prepared for the diffusion furnace system required to perform front and back junction formations, as included in the baseline process sequence. Firm fixed price quotations were received from four vendors. A final selection has been postponed until late 1981, and the specification could be substantially affected by results of the ion implantation junction formation study described in an earlier section of this report. Due to the planned delay, it will be necessary to obtain new quotations on the equipment regardless of specification development.

In addition, a preliminary E-Spec has been prepared for the Silox reactor which applies the CVD diffusion barrier required for this station. The acquisition of this apparatus may be obviated if results of the liquid dopant application studies, described in Section IIIB of this report, are positive.

2. AR and PR Application Stations

A vendor has resumed his efforts to establish process parameters for applying AR and PR (photoresist) coatings in a meniscus coating system. Conversations with the vendor indicate that progress is being made toward uniform coatings of the required thicknesses and that samples of coated material will soon be returned to use for evaluation. This coating technique is of interest because it can apply coating to only one side of the web and can be easily adapted to form part of an in-line processing system in the MEPSDU coat, bake, expose, develop, and etch sequence.

An unsolicited proposal has been received from a vendor for the design and fabrication of a device which will automatically dip a batch of web strips into the AR solution, withdraw the strips, hard bake the AR coatings, dip the batch of strips into the PR solution, and bake the PR coatings. The equipment would have the throughput capacity of the Westinghouse MEPSDU line. Acquisition cf this equipment has been deferred pending resolution of the meniscus coating application study.

3. Photoresist Exposure and Development Station

Several vendors have proposed equipment for the PR exposure and development station, but decisions on this equipment will be deferred until the technique used to apply the PR coating has been finalized.

4. Metallization Box Coater

An E-Spec was prepared for the metallization box coater required to perform base metal application (Ti/Pd) as included in the baseline process sequence.

Firm fixed price quotations have been received from five vendors. A final selection has been postponed until late 1981, and the specification could be substantially affected by results of the alternate metallization systems currently under investigation and described in an earlier section of this report. As with the diffusion furnace, the quotes will expire prior to final selection.

5. Metal Rejection/Plating Station

The selection of a technique for rejection of excess metal will not be made until the results of some of the process sequence studies, described in an earlier section of this report, are completed. These studies will determine if there is a need for, or an advantage to, the use of a plasma stripping unit to prepare metallized surfaces for electroplating.

A preliminary equipment specification was initiated for the electroplating system, but its completion has been deferred until work on the overall metallization process sequence selection has been completed.

6. Cell Separation Station

In the MEPSDU process sequence, the separation of the discrete solar cells from the dendrite-web matrix is accomplished by scribing the cell outline on the back of the web strip and fracturing out the individual cells. This scribing is accomplished using a Nd-YAG laser and penetrating the back surface of the web strip about one third its thickness.

An equipment specification for a laser scribe suitable for the MEPSDU throughput has been prepared, and copies were included in the preliminary design review data package.

The laser scribe system described in the equipment specification consists of the following elements:

1. Nd-YAG laser powered by krypton arc lamps.

2. Positioning fixture such that the web can be aligned to assure proper scribing directions and distances. This alignment is specified to be automatic - the operation constrained only to placing the web strip in a defined area.

3. A control unit which can be programmed to drive the fixture (or move the laser beam) through the required scribing path.

Item #2 is of prime importance in meeting the MEPSDU throughput requirement.

This equipment specification was sent to eleven manufacturers of laser equipment, and three firm quotes have been received. A formal technical evaluation team was established to rank the merits of the responses. A vendor selection meeting was held; and on the basis of the technical evaluation and relative costs, the Quantronix proposal was selected for contract negotiations. These negotiations will be completed in early September.

7. Cell/Module Test Stations

The equipment specification (E-Spec) for the module test equipment was expanded to include the requirements for the cell test equipment. Since the MEPSDU line will require testing a cell every five seconds and a module every half hour, it is rationalized that a single data acquisition system can be utilized to interface with both a small area and large area light source and their associated data channels.

Vendor quotations for the module/cell light sources and data acquisition systems have been received and reviewed. On the basis of the technical evaluation, relative costs, existence of off-the-shelf hardware/software packages, and delivery schedules, an equipment purchase order has been placed with Spectrolab, Incorporated. The order consists of an M.A.P.S.S. solar simulator (large area light source) and a semiautomatic cell test system to be interfaced with the M.A.P.S.S. data system.

8. Automated Cell Interconnect Station

An E-Spec has been prepared for the Westinghouse cell interconnect station. The specification defines the requirements for connecting individual photovoltaic cells together into an assembly for the fabrication of a photovoltaic module. The specified automatic interconnect assembly system will allow a clean, cost-effective method of building module cell matrices and connecting the required electrical busses to the cell strings.

Development work on the automated cell interconnect station equipment is being performed under subcontract to Kulicke and Soffa Industries, Inc. This work is described in Section IIID of this report.

D. Automated Cell Interconnect Station

Westinghouse has selected Kulicke and Soffa Industries, Inc., as its subcontractor for the design and development of MEPSDU equipment dealing with the automation of interconnection and assembly of its dendritic web silicon solar cells into modules. This subcontract deals with design, development, testing, and operation of equipment, and preparation of instruction manuals for the automated interconnect station.

The solar cell electrical interconnect configuration to be utilized by the interconnect station will be thin (.0015") aluminum tabs connecting metallized pads located on the front surfaces of each cell with the metallized rear surface of the adjacent cell. A major innovation in the Westinghouse cell interconnect station is the ultrasonic bonding technology to be used to join aluminum tabs to metallized cell surfaces.

The Westinghouse module, discussed in Section IIIA of this report, will incorporate 12 separate cell string assemblies. Each cell string assembly will contain 15 individual cells electrically connected in series. The 12-cell string assemblies will be positioned by the automated cell interconnect station equipment to form an array of 12 rows of 15 cells each, with nominal dimensions of 16 x 48 inches. The target machine cycle is 5 seconds/cell with a yield of 95% or better. The machine will also include substations for making subsequent

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parallel or bus bar electrical interconnections of the 12 individual cell string assemblies.

1. Interconnect and Cell Configuration

To improve the operations required for automatic interconnection of cells and connection of buses, K&S requested some minor modifications of cell and interconnect configurations during the past quarter which Westinghouse has agreed to. The modifications, and the reasons for them, are noted below.

a. Reduce the number of bond pads from 10 to 8 and increase the width of the interconnect tab to .045 inch. These modifications provide the following advantages:

● Increased distance between bond pads and the edge of the cell, which improves bonding and clamping, and reduces the possibility of cracking and chipping at the corners of the cell.

● Reduced number of bonds required which decreases bond cycle time.

● Improved interconnect handling.

b. Change the location of the trailing lead attachment on the cell string so that it corresponds to the second bond location of all other cells in the string. This will make it possible to attach the trailing lead at the second bond station with only minor mechanism and control modifications.

c. Make the interconnect that attaches to the leading cell of the string identical to the interconnect between the other cells of the string. This will eliminate the need to dedicate a cell to this purpose during tabbing, and also eliminate the need for associated microprocessor controls.

2. Interconnect Bonding Studies

During this quarter, ultrasonic bonding techniques for joining the aluminum interconnect to the cell metallization were evaluated. Bond pull tests were conducted using both a rotary seam bonding technique and a rolling spot bonding technique. Multiple bonds were made on each side of the back of the cell, and each finger was pulled independently. All pull testing was performed at a 90° angle to the bond with force applied at a rate of 32 grams per second until failure occurred.

a. Ultrasonic Rotary Seam Bonding

The bonds produced using the seam bonding technique appear satisfactory. A sample of pull test data from rotary seam bonds is presented in Table 8. However, the present bonding system has not yet proven fast enough to provide the required throughput rates without deterioration of bond quality and solar cell damage. In addition, steps must be taken to prevent the roller from engaging the cell between bond locations since this has been shown to have a deleterious effect on cell efficiency. In preliminary tests, the roller was lifted away from the cell by the action of a mechanical cam. Another technique used to accomplish the same purpose was the application of a protective mask between bond pads. For operation at the high speeds necessary to achieve the desired throughput rates, a more sophisticated method may be required to raise the roller between bonds and prevent it from engaging the bonds with excessive impact force, which could result in cell damage. Tests of the seam bonding technique also showed that bond quality depends on both the surface condition of the copper metallization and its adherence to the solar cell. In view of all these factors, much more development time and cost will be needed to make the rotary seam ultrasonic bonding technique meet contract requirements.

b. Ultrasonic Rolling Spot Bonding

To study ultrasonic spot bonding, a prototype bond station was constructed, adapted to a K&S Model 422 manual wire bonder, and controlled by a K&S Model 1418 computer. This system used a 20 watt Orthodyne Model #363-17 ultrasonic generator and transducer and a carbide wedge bonding tool specially designed by the Micro-Swiss Division of K&S. A photograph of the equipment is shown in Figure 7.

TABLE 8

ROTARY SEAM ULTRASONIC BONDING PULL TEST RESULTS

Cell No.	Avg. Pull Str. (gms)	Std. Dev.	Maximum (grams)	Minimum (grams)	No. Bonds Tested	Surface Prep.	Speed (in/sec)	Force (grams)	Power Setting
							Bond Parameters		
28,29	130	56.0	225	20	60	Steel Wool	.75	600	2
28,29	114	52.8	225	0	60	None	.75	600	2
17,20,27	133	42.5	200	25	66	Steel Wool	.75	500	2
17,20,27	76	42.0	165	5	68	None	.75	500	2
10	127	49	210	40	20	Steel Wool	.58	600	1.7
10	101	52.2	205	25	30	None	.58	600	1.7
22,27	121	42.0	215	20	30	Steel Wool	.58	500	1.7
22,27	84	50.7	165	0	20	None	.58	500	1.7
20	102	58.9	195	40	10	None	.58	500	2

NOTE: All bonds made to back side of cells using .0015" thick aluminum (1145-0) interconnect material.

Figure 7. Prototype Spot Bonding System

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In this technique, unlike conventional ultrasonic spot bonding, the tool descends on the work at an angle so that, initially, only a portion of the tool contacts the aluminum interconnect ribbon. As ultrasonic power is applied, the tool rotates or "rolls" through a small angle, progressively bonding the entire bond area as is shown pictorially in Figure 8.

The bonds produced by this type of spot bonding tend to exhibit more uniform and slightly higher average strength than those produced by rotary seam bonding, even when a lower bond force is applied. A sample of pull test data from rolling spot bonds is presented in Table 9.

A mock-up prototype of a station has been constructed to verify that the multiple head arrangement does not cause problems such as deterioration of cell efficiency.

c. Machine Bonding Technique Selection

The rolling spot bonding technique was selected for use in the MEPSDU solar cell tabbing and string machine for the following reasons:

- Bond Cycle Time - To achieve the minimum throughput rate required with the seam bonding system, the seam roller would have to move from bond to bond at high speed. However, the relatively high mass of the seam roller, as compared to the spot bonding head, makes this high speed movement more difficult.

- Cell Efficiency - Basically, the seam bonding technique accomplishes bonding by a continual rolling motion of the bonding tool. Consequently, additional steps must be taken to prevent the tool from engaging the cell between bonds since this has a negative effect on cell efficiency. To ensure proper operation at the high speeds necessary to meet throughput requirements, this additional action would have to be accomplished in a
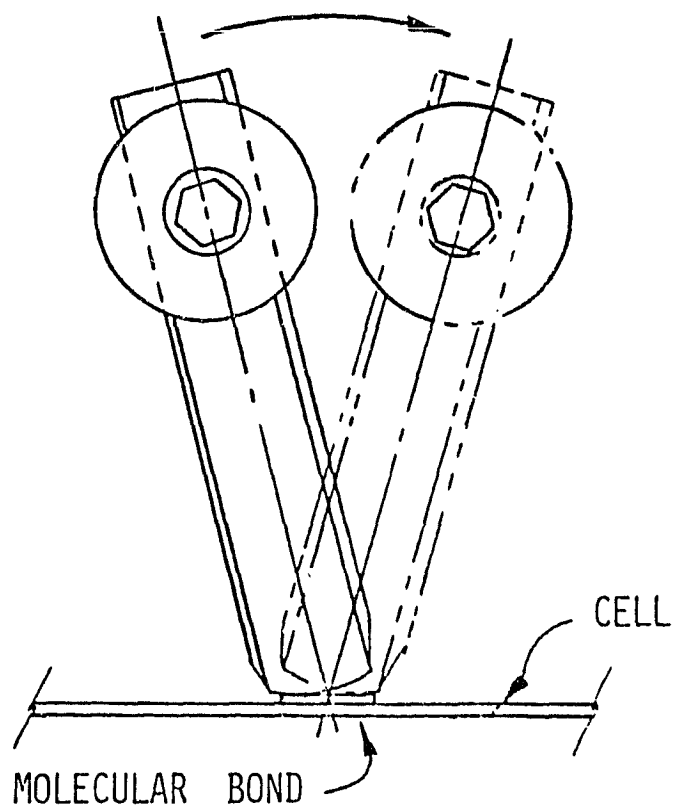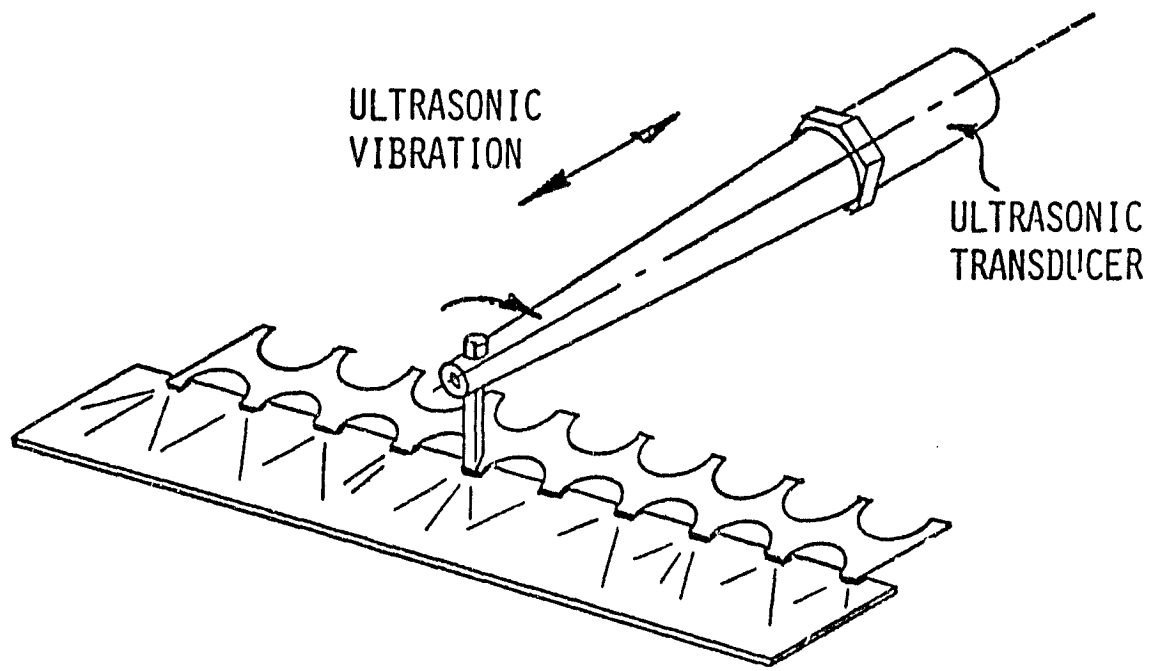
ULTRASONIC
VIBRATION

ULTRASONIC
TRANSDUCER

CELL

MOLECULAR BOND

Figure 8. Rolling Spot Ultrasonic Bonding

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TABLE 9

ROLLING SPOT ULTRASONIC BONDING PULL TEST RESULTS

CELL GROUP	CELL NO.	AVG. PULL STR. (GMS)	STD. DEV.	MAXIMUM (GRAMS)	MINIMUM (GRAMS)	NO. BONDS TESTED	SURF. PREP.	BOND	PARAMETERS		CELL SIDE	REMARKS
								TIME M SEC	FORCE (GRAMS)	POWER SETTING		
C1016	6B	110	62.6	175	20	10	AS IS	150	450	5	TOP	CU NON UNIFORM APPEARANCE – 1 CELL
C1015	28B 32A 22B [379]	156	44.7	225	60	38	AS IS	150	450	5	TOP	CU CLEAN & UNIFORM 4 CELLS
C1016	6B	137	54.0	225	50	29	AS IS	150	450	5	BACK	CU NON UNIFORM APPEARANCE – 1 CELL
C1015	28B 32A 22B	168	30.2	225	105	68	AS IS	150	450	5	BACK	CU CLEAN & UNIFORM 3 CELLS

NOTE: All bonds made using .0015" thick aluminum (1145-0) interconnect material.

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manner that would also avoid excessive tool impact on the cell. The spot bonding tooling engages the cell only at the bond locations and, therefore, should not cause any decrease in cell efficiency.

● Multiple Heads - To achieve the required throughput with present equipment, it may be necessary to use two bonding heads. The lower mass of the spot bonding head would permit the use of two parallel heads in the same bonding station. This would prove difficult with rotary seam bond tooling.

● Power Range - Present seam bonding equipment operates at the very low end of its capability which makes adjustment both more difficult and more critical. On the other hand, the spot bonding equipment operates at mid-range which is more stable.

● Bond Force - Spot bonding can be accomplished with less bond force than seam bonding. As a result, spot bonding subjects the solar cell to less localized stress which should result in less damage to cells.

● Tooling Flexibility - Tooling changes with the seam roller are limited and expensive since the entire horn must be changed. The spot bonding tools are simple carbide wedges which are inserted into the horn and may be changed easily. In addition, the carbide wedge wears longer than the hardened steel seam roller.

● Cost - The ultrasonic system and tooling required for the seam roller cost approximately ten times more than the ultrasonic generator, transducer, and wedge used for spot bonding.

3. Machine Configuration

Figure 9 shows a drawing of the current automated cell interconnect machine configuration. Major machine components and substations are identified on the drawing. The basic changes incorporated into the configuration during the past quarter are:

- The use of rolling spot bonding heads in place of seam bonding equipment

- The addition of a trailing lead feed station to bond aluminum interconnects to back side of the final cell in each 15 cell string assembly

- The reconfiguration of the module area to facilitate production flow to the proposed bus attachment and layup stations which Westinghouse is considering for addition at the discharge of the machine.

Figure 10 shows the proposed scheme for the bus attachment and layup stations.

Layouts for the cassette unload station have been completed, and detail drawings are being made. The station holds up to four cassettes, each typically containing 25 cells. A specific cassette design is being investigated for cost and compatibility with other Westinghouse MEPSDU operations.

Layouts for the multiple spot bonding head and work on the interconnect (ribbon) feed operation have been initiated. Preliminary layouts for the first half or tabbing section of the machine (see Figure 9) have been prepared. These layouts include the mounting frame for the stations in this area. Also, work has begun on design of the cell alignment substation.

A mock-up of a "walking beam" type string conveyor has been made. A small mock-up for simulating a belt conveyor is under construction. These mock-ups will aid evaluation of problems which may be encountered in handling the dendritic web cell during the stringing operation.
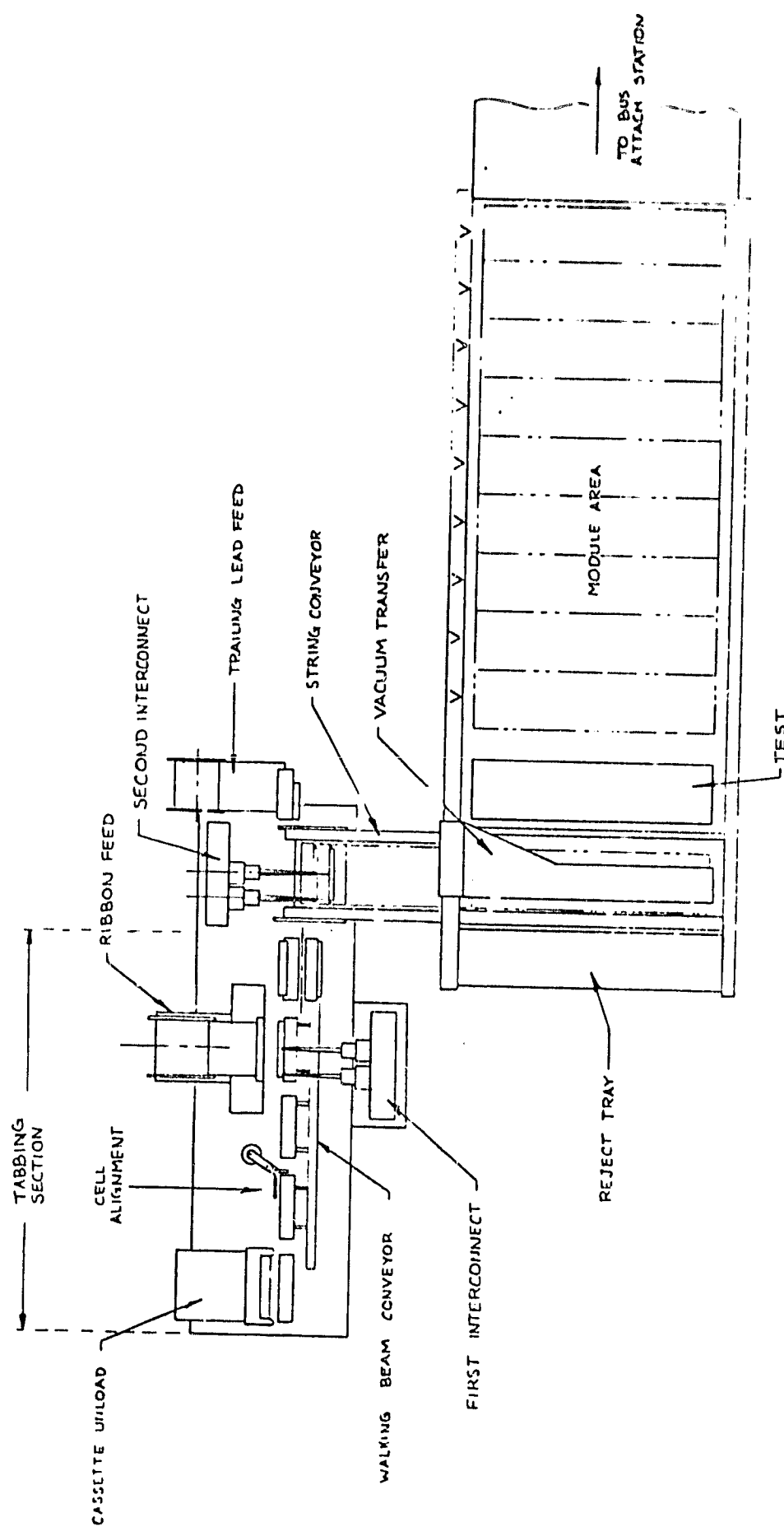
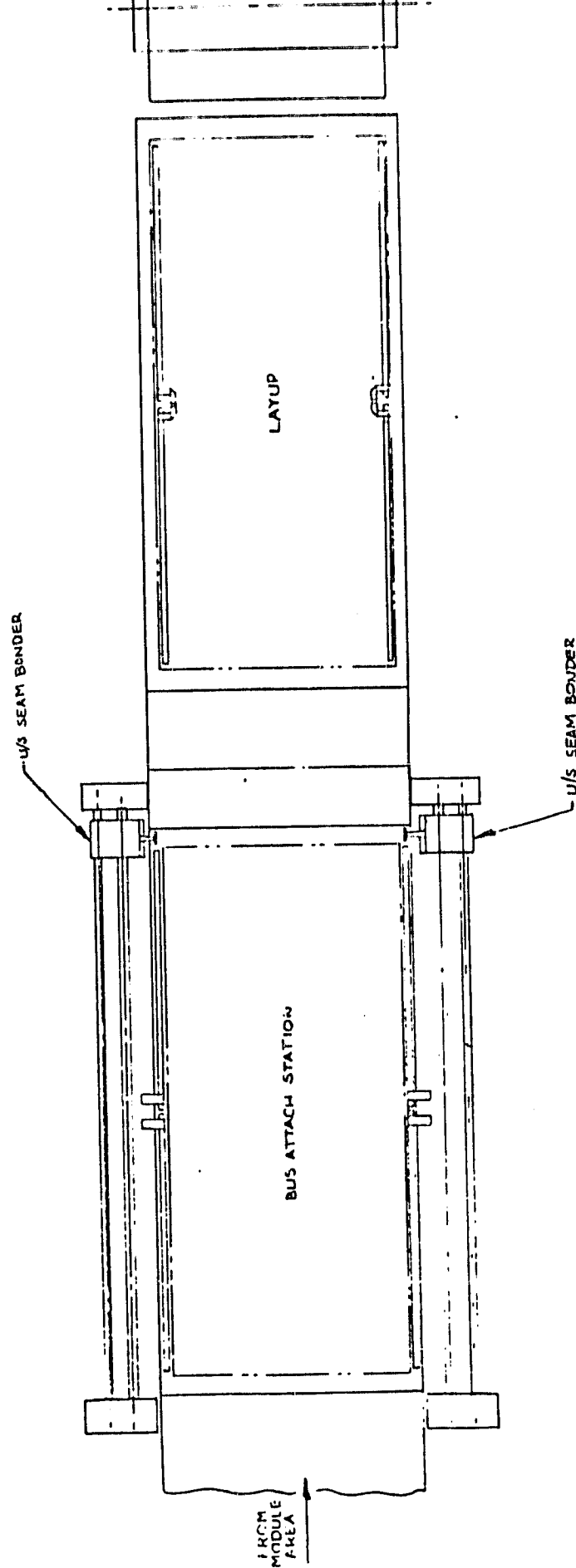Figure 9. Automated Cell Interconnect Machine Configuration

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Figure 10.   Proposed Scheme for Module Bus Attachment and Layup Stations

E. Preliminary Cost Analysis

   1.   Background

The baseline process sequence for fabricating solar modules from dendritic web silicon for the MEPSDU has been analyzed using SAMICS methodology. Since the MEPSDU facility is designed to have a 1 MW/yr production rate, the first simulation was based on the throughput required for this production. To determine if the process sequence is also an efficient step toward high volume-low cost production, a similar analysis was made for an automated production facility having a 25 MW/yr production rate. Throughout this report these two simulations are referred to as the M-Process (1 MW/yr) and the P-Process (25 MW/yr).

For ease in comparing the costs of the individual steps within the process sequences, the 1 MW/yr and 25 MW/yr simulations follow the same sequence steps and use the same step referents.

Table 10 is a listing of the process steps and referents used for these two simulations. The thirteen individual steps follow a natural grouping of sub-tasks within the process sequence.

The data used in the Format A's for the two processes were based on recent vendor quotes for capital equipment and materials. The material usage was based on calculated requirements and pre-pilot facility experience.

   2.   Assumptions Used in SAMICS Cost Analyses

   ●   3 shift, 345 days per year operation (4.97×10^5 operating minutes per year)

   ●   The modules fabricated in both the 1 MW/yr M-Process and the 25 MW/yr P-Process facilities have nominal dimensions of 40 cm x 120 cm (16" x 48").

   ●   These modules are assumed to produce 60 watts at 28°C and 100 mW/cm^2 insolation. This is based on module performance calculations presented in Table 1 of this report.

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TABLE 10

PROCESSES AND REFFRENTS USED IN SAMICS COST ANALYSES

Process #	Referent	Process Name
M1/P1	CLENWEB	Pre-Diffusion Cleaning
M2/P2	DIFFWEB	Boron Diffusion
M3/P3	BSF	Phosphorous Diffusion
M4/P4	ARPR	Application of Antireflective Coating and Photoresist
M5/P5	GRIDDE	Expose, Develop, Etch
M6/P6	METWEB	Metallize
M7/P7	REJPL	Reject/Plating
M8/P8	TESCEL	Cell Separation and Test
M81/P81	CELYD	Yield Dummy for Cells
M9/P9	INTCON	Cell Interconnection
M10/P10	LAMMOD	Module Lamination and Test
M101/P101	MODYD	Yield Dummy for Modules
M11/P11	CRAMOD	Crating

- The M-Process assumes a throughput rate of 200 cm^2/min of usable web (99.4 x 10^2 m^2/yr).

- The P-Process assumes a throughput rate of 5000 cm^2/min of usable web (2.485 x 10^5 m^2/yr).

- The strips of dendritic web input into both processes are 42 cm long by 2.7 cm wide. From these strips four 2.5 cm x 10 cm (nominal) cells will be fabricated. The cost for the silicon used in the Format A input includes all losses due to non-utilization, e.g., dendrites and strip end losses.

- Yields for the process are taken into account in two steps in the sequence. First, after cell test and second, after module test. For ease in computation, these are listed as two separate, no-cost, steps in the process sequence. In the present simulations, the overall cell yield is assumed to be 90% and the module yield is 95%. All other process steps are assumed to have 100% yield.

- All machines are listed as being operational 100% of the time. The various pieces of equipment have been sized such that the required throughput can be obtained assuming industry experience in downtime. Any major maintenance will be carried out during the 20 days/year downtime.

- Waste materials (organics, acids, oils, etc.) are disposed of by a local contractor. The Format A inputs for this disposal are derived from a vendor quote.

- In extrapolating from the 1 MW/yr M-Process to a 25 MW/yr P-Process, a highly automated factory was assumed. This automated factory concept increases capital cost but greatly decreases labor input. In general, the material usage was scaled very nearly proportional to the production rate with very small savings in usage assumed. This is a realistic assumption since much of the expensive materials (e.g., glass, laminating material, etc.) are area related and are absolutely proportional to production rate.

3. Results and Conclusions

Using the required Format A, B, and C data, SAMIS simulations were carried out for both the M (1 MW/yr) and P (25 MW/yr) processes. Results are summarized in Table 11, in which the value added for each process step as well as the total production cost per watt are itemized.

The simulation data indicates that extrapolation of the 1 MW/yr MEPSDU process to a 25 MW/yr production facility leads to a cost effective manufacturing sequence which essentially meets the DOE/JPL cost goals of $0.70/watt (1980 dollars) in 1986. The scaling was based on the assumption of a highly automated process, both within a given step and between process steps. This assumption reduces the labor content of the product cost. The material costs were scaled at a ratio of 19:1 usage factor for a 25:1 production ratio. Therefore, only minimal savings are assumed for material costs in the scale up.

F. Documentation

All programmatic documentation specified in the Westinghouse MEPSDU contract has been submitted in accordance with schedular requirements. A list of the programmatic documentation and submittal dates are compiled in Table 12.

G. Activities Planned for Next Quarterly Reporting Period

The fourth quarter of the Westinghouse MEPSDU program covers the period September 1, 1981 through November 30, 1981.

TABLE 11

SAMICS COST ANALYSIS RESULTS FOR 1 MW/YEAR (M-PROCESS) AND 25 MW/YEAR (P-PROCESS) FACILITIES*

		1 MW Process	25 MW Process
1.	Pre-Diffusion Cleaning (including Input Silicon Dendritic Web)	.539	0.320
2.	Boron Diffusion	.201	0.032
3.	Phosphorus Diffusion	.190	0.027
4.	Application of Antireflection and Photoresist Coatings	.230	0.015
5.	Exposure/Development/Etch to Form Grid Lines	.201	0.018
6.	Metallize Web	.450	0.038
7.	Rejection/Plating	.410	0.039
8.	Cell Separation and Testing	.770	0.035
9.	Cell Interconnection	.277	0.027
10.	Module Lamination and Testing	.381	0.141
11.	Crating of Modules	.116	0.026
	TOTALS	3.77	0.72

*Simulated at 28°C, AM1, 100 mW/cm^2

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TABLE 12

PROGRAMMATIC DOCUMENTATION SUBMITTAL STATUS

ITEM	SUBMITTAL DATE(S)
1. COST ESTIMATES	
a. Baseline	December 17, 1980
b. Revised	May 22, 1981
2. SCHEDULE ACCOMPLISHMENT REPORT/FINANCIAL REPORT	December 17, 1980 January 14, 1981 February 16, 1981 March 16, 1981 April 16, 1981 May 16, 1981 June 16, 1981 July 16, 1981 August 17, 1981
3. PROGRAM PLAN AND WBS	
a. Original	December 17, 1980
b. Revised	May 22, 1981
4. MONTHLY TECHNICAL PROGRESS REPORT	January 15, 1981 February 15, 1981 March 15, 1981 April 15, 1981 May 15, 1981 June 4, 1981 July 6, 1981 August 6, 1981 September 8, 1981
5. PRELIMINARY DESIGN REVIEW PACKAGE	February 19, 1981
6. MODULE DESIGN REVIEW PACKAGE	June 30, 1981
7. QUARTERLY TECHNICAL PROGRESS REPORT	March 15, 1981 June 15, 1981

Although module design work has been essentially completed, hailstone impact tests will be completed during the next quarter. If these tests identify the need to incorporate edge protection, the required modifications will be made to the module drawings.

Process sequence design and MEPSDU equipment work will highlight activities on the Westinghouse MEPSDU contract during the next quarter. In particular, the MEPSDU process sequence will be firmly established during this period. This sequence will be the current "baseline" sequence as modified to incorporate any improvements which have been qualified in our current process sequence investigation tasks.

Work on the Kulicke and Soffa subcontract in the fourth quarter of the project will continue on machine concepts and individual stations. Work in the control system area will focus on determining the components to be used for controlling the automated functions of the machine. Investigation of the hardware and software requirements of the machine to be developed and built will proceed, and decisions will be made on procurement of specialized items to be used depending upon lead times for these components. The order for the automated cell interconnect station hardware will be placed early in the quarter in compliance with the recently approved equipment specification.

A JPL/Westinghouse workshop has been scheduled for September to review the results of the SAMICS economic analysis. It is anticipated that comments and suggestions from this workshop will result in modifications that will require an updated analysis which will be performed during the upcoming quarter.